Naval Hybrid Power Take-Off and Power Take-In – Lessons Learnt and Future Advances

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SYNOPSIS

With the ever tightening of budgets and legislation, new vessel builds are facing tough times. The future maritime industry requires more efficient vessels to minimise ship operational costs with cleaner technologies that meet stringent environment regulations, reduce greenhouse gas emissions, specifically carbon emissions. Emissions reduction continues to be high on the agenda for the marine industry, it is responsible for about 2.5 percent of global greenhouse emissions[1] and is under great pressure to reduce its environmental impact. With pressure comes the opportunity to incentivize innovation, developments and implementation of energy efficient measures, both design and operational. Naval propulsion systems are no different from other industries, and the industry is exploring ways to optimise propulsion and electrical power generation systems architecture for better performance and efficiency. Electric technology plays a leading role.

The paper will:
- Provide a brief overview about the hybrid propulsion concept, with key electrical, mechanical qualities and issues
- Describe different designs configurations and performances of hybrid propulsion systems from demonstrated and operational systems in the commercial and naval world
- Cover the lessons learnt in technologies and controls used on such systems
- Examine future architectures including energy storage and explore the benefits and the flexibility these can bring to the hybrid propulsion sphere.

1. Introduction

Efficiency management on a vessel must involve an integrated solution that extends across the entire operation of the ship systems as well as the fleet. One option is for ships to reduce fuel consumption by slowing down, but this comes at the expense of increased voyage or mission duration. However, the development of certain technologies and adequate selection of power and propulsion systems such as innovative Power Take-Off and Power Take-In (PTO/PTI) to meet the ship's operational profile and service load can result in significant fuel savings and operational flexibility while remaining on mission. PTO drive train technology can also contribute to reduce maintenance cost and increase reliability.

Several hybrid systems have been either introduced into naval service, are in build or are at an advanced stage of land based testing and there have been lessons learnt about the system implications of incorporating this technology in its various forms. These include torque management and its impact on propulsion engines, current management and its impact on power quality and selectivity, voltage management, particularly in transformerless applications, harmonic management, both of differential and common mode harmonics, and the implications of different approaches to load sharing.

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[1] 3rd IMO GHG study

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The maturing of hybrid technology means that it is ready to move into more advanced areas, such as energy management, to release system benefits such as transient smoothing, rapid blackout recovery, blackout prevention, and architectural benefits, such as fewer prime movers and higher efficiency.

2. Propulsion system selection criteria

The diverse operational profiles of modern naval vessels lead to a trade-off between efficiency and adaptability and have led to a growing variety of power and propulsion architectures:

- Full electric power and propulsion, mechanical propulsion, or a combination of both, forming a hybrid system.
- Power generation with combustion engines, supplemented by energy storage or a combination of both.
- AC or DC electrical distribution.

Whilst hybrid propulsion is not new, it is being increasingly employed for vessels operating a low proportion of time at full speed and spending significant periods at low power, e.g. below 40-50% of their top speed. Typical applications of hybrid power and propulsion systems are naval frigates. On such vessels, the auxiliary load is only a fraction of the required propulsive power; it could be claimed that the operating characteristics associated with the full electrical power conversion leads to increased fuel consumption for full electric power and propulsion systems (Greertsma, 2017). The extra electrical equipment also leads to increased weight, size and cost (Castles, 2009) Therefore, ships that frequently operate at low speed can benefit from a hybrid propulsion system.

The latest hybrid solutions combine main diesels or a gas turbine engine with an active-front-end, variable speed converter in combination with an induction motor, that can operate as both a motor (PTI) and a generator (PTO), to drive a controllable or fixed pitch propeller, either through a gearbox or direct. PTO/PTI can also improve fuel efficiency by harnessing excess mechanical energy from a vessel's propulsion shaft. Electric propulsion systems avoid running the main engines inefficiently in part load, resulting in fuel savings of up to 5-10 percent. Advancement in design of electrical machines and power electronics converters and their controls offers a flexible range of speeds and modes of operation. Overall, electrical machines and variable speed converter drives can achieve over 95 and 97 percent efficiency respectively and can maintain high levels across the full operating speed range and be bi-directional.

3. Overview of advantages and their application

There are a number of hybrid applications that have either recently been brought into service or that are currently in build and these illustrate the range of potential benefits that a hybrid system can bring. No single application makes use of all those features but each selects the range of benefits that is most suited to their operational role. The benefits and the vessel types are illustrated in Table 1:

	Direct Drive Frigate Anti-Submarine Warfare (ASW)	**Direct Drive Commercial**	**Geared Auxiliary Vessel**	**Geared Light Frigate**	**Geared Assault Ship LHD/LHA**
Reduced Engine Count		✓	✓		
No Gearbox	(✓)	✓			
Efficiency	✓	✓	✓	✓	✓
Reduced N&V	✓			(✓)	
Electrical Energy	(✓)	✓	✓	✓	✓
Survivability	✓			✓	✓
Shore Supply / Disaster Relief				✓	

Table 1 Example Recent Hybrid Systems

3.1 Example Vessel Types

The first vessel type is the Anti-Submarine Warfare (ASW) Frigate. This is focused on the low Noise and Vibration (N&V) capability that a direct drive electric motor can offer for lower speed operation, with the gearbox decoupled from the propeller shaft. This approach was pioneered on the Royal Navy's Type 23 Frigate and has been adopted on an increasing number of ASW designs around the world. However, the electric drive has the secondary benefit of excellent range on efficient electric propulsion and can offer a reversionary source of electric power when combined with PTO mode.

The second form of PTI/PTO hybrid is employed on direct drive diesel commercial vessels. Here a direct drive electric motor can provide low speed propulsion using efficiently loaded diesel generator (DG) sets and can also replace those sets as a source of electrical power, via PTO, once the main propulsion engines are engaged. The PTO can also serve as a boost source of electric power in addition to the DG sets if additional electrical power is required.

This ability to serve as loiter type propulsion as well as a stand-alone source of power or an additional source to share on the bus has been exploited in the third example of hybrid, for auxiliary naval vessels. In this case the PTI/PTO machine is connected to the propulsion gearbox of a medium speed diesel and is combined with a controllable pitch propeller. This has given enormous flexibility to the power and propulsion system, enabling the optimisation of the number of prime movers on board while still providing four independent sources of electrical power and four independent sources of propulsion power for normal operation.

A similar approach is taken in the fourth example, that of the Light Frigate. However, in this case the hybrid drive is not used to decrease the number of prime movers but to increase the number of options available to command for delivering power and/or propulsion. In this case the electric drive is shock hardened to enhance survivability and can also be configured to serve as a frequency converter between the ship power system and the shore to support disaster relief operations or simplify shore supply.

The fifth example type is that of a large assault ship that incorporates a gas turbine propulsion mode but also retains a significant lower speed electric capability. In this type of vessel too, the geared electric propulsion is shock hardened to provide additional survivable capability but the key benefit is the significantly enhanced vessel efficiency that is achieved for low speed operation.

3.2 Functionality and advantages

Reduced Engine Count

This refers to the possibility of having fewer engines installed, as the system is taking full advantage of the PTO used as a source of electrical power contributing to the overall ship power generation. PTO output can be substantial and comparable to an output of a diesel generating (DG) set.

No Gearbox

This relates to the ability of the system to operate without a gearbox. This improves the maintenance regime of the gearbox, the efficiency of the drive train and the noise signature (highly relevant to ASW frigate).

Efficiency

Energy efficiency has always been an important factor to minimise ship operational costs. Hybrid-electric systems allow naval vessels to optimize their propulsion power to suit each operational scenario – they enable economical operation at loitering or patrolling speeds of up to ~18 knots, covering most of the operating profile of the ship and having the capability to attain sprint speeds (usually around 30 knots) on the gas turbine when it is switched in.

Further efficiencies can be achieved, such as the ship's automation system optimising the efficient loading and number of running engines for PTO and PTI modes. In turn, this can reduce maintenance requirements and associated costs.

A typical comparison of electrical power and propulsion system losses, in PTI are given in Table 2.

Prime mover input	Generator	Switchboard	Supply transformer	Propulsion converter	Propulsion motor	Shaft power
100%	3 to 4%	0.2%	1.5 to 2%	1.5 to 2%	3 to 4%	90.8 to 87.8%

Table 2 Efficiency Comparison

In mechanical mode, propulsion diesel or gas turbines must run at high speed for best efficiency so a high ratio reduction gear is essential to obtain any economical propeller speed. Efficiencies of such engines are generally below 50% for propulsion use.

Reduced N&V

Naval vessel design can be driven by ASW requirements, with a need for low N & V signature and very quiet operations at slow to medium speeds: “Detect the enemy before they detect you”. Electric propulsion systems can meet highly demanding acoustic signature specifications, in part because gearboxes and their auxiliaries are not required. This allows naval vessels to operate with lower risk of detection.

Advances in electrical machines and their associated converter drives in electromagnetic design, waveform smoothing, anti-vibration technology along with shock proof motors achieve a much quieter operation than can easily be obtained by traditional mechanical systems.

Electrical Energy

Hybrid power and propulsion systems have most of the advantages of a central power generation concept which can service the propulsion and all other ship loads. Power generation (number of DG sets running and their respective loadings) can be adequately regulated to meet ship’s power demands.

In addition, hybrid can take advantages of the PTO mode to generate power, optimally loading the propulsion engine with some DG sets switched off.

To optimise the system, all degrees of freedom should be bought into one function of meeting the most efficient mode of operation and the ships demands for propulsion and electrical power in all operating profiles.

Survivability

Survivability is a complex subject as it covers redundancy, high integrity, fault-tolerant systems, spatial separation, and manual backup systems to ensure continuity of vital services during major disruptions associated with battle and damage control operations. Hybrid propulsion systems are configured to take advantage of the best of both worlds of propulsion: conventional mechanical and electric. They can maximize system integrity, minimize interdependencies and tolerate simultaneous disturbances to both the machinery and the control system. With a corresponding capable electrical distribution protection scheme, hybrids have the ability to fight through combat damage, such as missile detonation. The protection scheme can sense, isolate, and quickly compensate for major disruptions, e.g. the electrical propulsion motor connected to the diesel or gas turbine gearbox can run the propeller separately or in parallel. As described above, engine/generator sets can be out of operation without major consequences to the operation of the vessel, and main engine and PTI can be operated independently of main propulsion gear thus giving a high degree of survivability, redundancy and flexibility of operation.

PTI can have further redundancy in that electrical propulsion converters can comprise multiple channels and motors can be multi-phase in both shaftlines.

Shore Supply / Disaster Relief

Ships with a hybrid power and propulsion system that includes PTI/PTO converters are capable of transmitting power in either direction and, when they are alongside in port, can be reconfigured for use as grid frequency converters. This enables the import of power from a grid, of either 50Hz or 60Hz and permits the export of power to the shore at either frequency. This can be particularly helpful in a disaster relief situation where shore based sources of power may have been disabled.

Thus, the flexibility and range of PTI/PTO hybrids have been illustrated in their application to a range of recent vessels. However, this flexibility brings with it considerable technical challenges for the system, some of which are considered below.

4. System Implications of PTO

There are a number of system related issues that arise when integrating PTO with a vessel. Some of these issues arise out the fact that PTO is tying one system, the propulsion system, to another, the electrical distribution system. Others relate to the fact that a new technology is being used as a source of energy (i.e. based on solid state silicon) that has different underlying behaviours from the conventional technology (based on rotating copper and iron). Some of these issues have already been covered in previous papers (e.g. Simmonds, 2016). However, there are some additional aspects that are worth considering.

4.1 Shaft Load Dynamics

Significant torsional load changes on a propulsion shaftline are typically gradual with the changes taking place over a number of seconds.

Torsional load on a generator shaftline can change very suddenly with a large load application or rejection on the electrical distribution system. For this reason, engines that are designed to operate as the prime mover of a generator have demanding performance standards applied by the class societies, e.g. 33% instantaneous load step, and the engine must only dip in speed by a defined amount to maintain system frequency and recover to nominal speed within a defined (short) period (DNV-GL, 2015). These severe performance standards are not normally applied to propulsion engines and it may be expensive to do so.

The PTO system uses a propulsion engine as the prime mover for a generator. This can present challenging system integration problems but there are a couple of factors that can be used to mitigate these. Firstly, it should be noted that the propulsion engine typically has a significantly higher rating than a generator, so the load steps involved represent a small proportion of the propulsion engine's full capability. Secondly, the converter itself is able to limit the impact of a load step on the electrical system by limiting the rate of change of power it demands from the engine. Even though the engine will dip in speed as it takes up the load, the converter can protect the electrical system from the full effect of the frequency variation, though the voltage will clearly dip in these circumstances. If properly integrated, the converter can balance the demands of the system with the limitations of the engine performance to provide a fully compliant overall quality of power solution.

4.2 Current Management for Selectivity

A conventional generator has the natural property of delivering a significantly higher current than its maximum load current when a short circuit is applied. Sensing-circuit and protection relays deduce that there is a downstream fault and open associated circuit breakers to isolate this fault. A converter, however, does not have this natural property. It is normally sized to deliver its load current with only a small overload capability. Where the protection settings can be integrated with the electrical power system configuration this can be managed with a simple current clipping feature in the converter (Simmonds, 2016). However, where a simple, conventional protection scheme is used the converter must be designed to deliver the correct fault current in the event of a fault. This is illustrated in Figure 1. This shows current and voltage traces during a fault event.

When the fault is first imposed the current clipping feature in the drives provides a simple, fast acting limiting mechanism that prevents the converter from having to trip and the network bridge keeps supporting the bus voltage. However, this does not provide the defined overcurrent on which the system selectivity is based. The converter therefore switches, within a few cycles, to its fault current delivery mode which it sustains for a defined period, or until a downstream relay IDMT (inverse definite minimum time) curve is activated, thus clearing the fault. The converter then switches back to voltage control and restores the system volts to the correct level. This approach means that a simple, conventional protection scheme can still be used to achieve selectivity, provided that the fault current capability of the converter is respected.

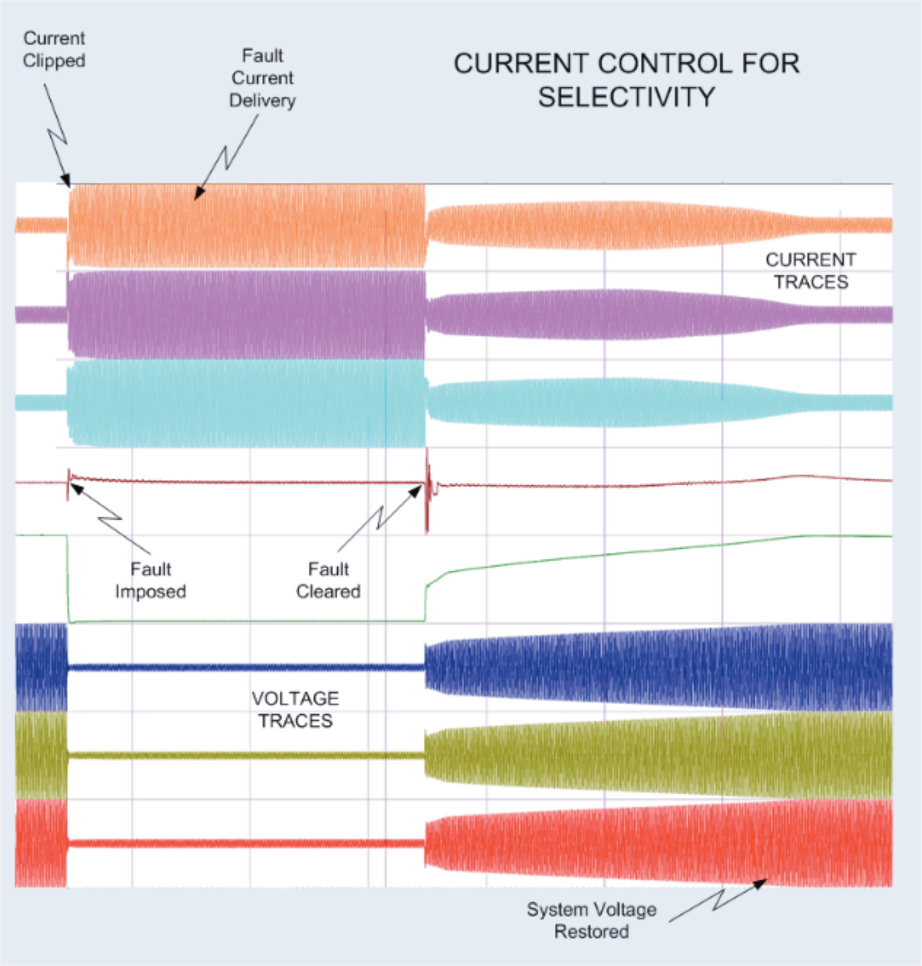

Figure 1 Current Control for Selectivity

4.3 *Voltage Management for Capability*

One of the limiting factors that applies to a converter in PTO mode is its ability to deliver the correct voltage to ensure the nominal load can be delivered at the nominal power factor (typically 0.8) through the full permitted voltage range of the system bus. The factors affecting this are illustrated in **Figure 2**. The first vector defines the nominal system voltage (e.g. 690Vrms, 440Vrms etc.). This bus voltage is permitted to vary within class society Quality of Power Supply (QoPS) limits, typically -10% to +6%. The converter must deliver those volts to the system via its output filter, which imposes its own volt drop that is related to the power factor of the load being supplied. This then defines the bus voltage (Vrms) waveform that must be delivered by the network bridge. This is synthesized by the bridge which must be able to generate the peak waveform using a modulation strategy that in turn can only use a proportion of the available DC link voltage. That DC link voltage is generated by the machine bridge using the motor/generator as the power source. In general, it is preferred that the average DC link voltage should be lower, rather than higher, so the DC link voltage control needs to manage the volts to ensure that the PTO waveform can always be generated, without holding an excessive voltage margin or exceeding the maximum permitted DC link voltage.

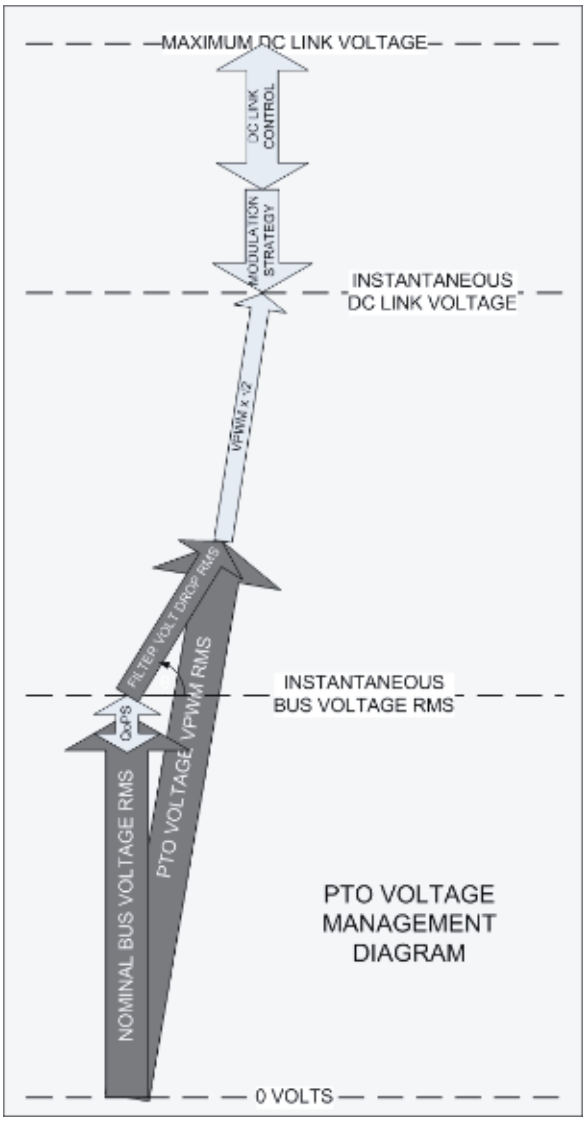

Figure 2 – Voltage Management

4.4 Harmonics

A converter imposes time harmonics on the network to which it is connected. On a three-phase system where a converter has a Diode Front End (DFE) network bridge then those harmonics occur at $F_0(6N\pm1)$, where F_0 is the fundamental frequency and N is an integer. For an Active Front End drive (AFE) the network bridge uses transistor switching and the harmonics are dominated by the Pulse Width Modulation (PWM) switching frequency and its multiples. This is normally a high value, 10 to 50 times F_0 or more. For a modern PTO system, the power source is an AFE network bridge. However, the AFE will incorporate a network filter which will reduce the PWM element to a small percentage of the waveform. This is typically a few percent and is therefore normally within the class society voltage Total Harmonic Distortion (THD) limits. The system load, however, may include DFE converters and these are typically unfiltered. Where a system is generator fed, the sub-transient reactance of the generator will tend to reduce the impact of these harmonic currents on the system voltage. This is not the case for a PTO system and the PTO filter is unlikely to be targeting the DFE harmonics. This means that for a PTO fed system the total amount of distorting load on the system must be carefully managed to ensure the system stays within limits in the worst-case configuration of the power system.

Further complication can be introduced where different AFE drives are used in the same system (Bellamy & Salter 2016) whose AFE filters can potentially interact. It is therefore imperative that the power system is as accurately modelled as possible during the design phase to minimise these risks.

Another element of distortion that needs to be managed is common mode distortion. This occurs as a result of switching on the DC link and can impact the wider distribution system where transformerless converters are used. The PTO converter must therefore include a common-mode filter to minimise interference in the system. Where high power converters are used, when combined with cable capacitance to ground and the capacitance of the motor/generator, these filters mean that the historic standards of very low capacitance to ground at the point of coupling are unachievable in practice. This is a subject in its own right and will not therefore be covered in further depth here.

4.5 Load Sharing

In a traditional ship's supply system, the frequency is controlled by a relatively low bandwidth engine governor and the voltage by an automatic voltage regulator (AVR) acting through the (relatively slow response) of the generator field windings. For a PTO system, the control bandwidth and precision are vastly superior to the traditional generator. Exact, high response control of frequency, voltage, active and reactive power are possible. In this context it is possible to shape the response of the PTO system depending on whether or not it is sharing with a generator and what the overall state of the system is. More advanced algorithms can be implemented within the converter software that go beyond simple proportional sharing and permit overall performance optimisation for the system. When this capability is combined with a converter energy store that is independent of the dynamic limitations of the mechanical system then further system capability benefits can be released. This is considered in the next section.

5. Propulsion Converter as Energy Management Unit

Over the past decade, there has been rapid technological development in energy storage technologies and a fall in their costs, particularly the cost of lithium batteries. The volume and trends of the electric car industry have helped the drive of volume production, compactness, reliability, longevity and the overall acceptance as an energy source. The advantages that an energy storage system bring onboard a vessel are well understood in terms of:

- Fuel savings (between 10 to 20%, depending on the type of engines, energy storage capacity and overall electrical ship system) and reduced emissions.
- Increased redundancy and efficient operations.
- Reduced engine maintenance (due to more coordinated operation and fewer running hours resulting in reduced maintenance), to the point that it is even possible to run on a single generator during some conditions; all other DG sets are either switched off or on standby.
- Increased performance. The electrical system will be more responsive and the charged energy storage systems will come on-line much faster than prime movers and will also not depend on many auxiliaries and systems configurations; this mode is highly advantageous during critical operations.

However, the benefits of energy storage come at a price in terms of volume and vessel infrastructure. Energy is not stored in convenient 60Hz units that can match a normal AC distribution bus. Even if that bus is changed for a more exotic DC distribution system a typical energy store will reduce its voltage output as it discharges and is therefore unsuitable for direct connection to a DC bus unless all loads have the complexity of being able to manage the consequent voltage droop. In reality, therefore, all energy stores need some form of power electronics to interface to the DC or AC distribution bus. Such power electronics add cost, take up volume, need auxiliary services and are typically connected to the distribution bus via a dedicated protective device, such as a circuit breaker.

However, with the advent of modern PTI/PTO propulsion converters a device already exists on the ship that is able to invert power from a DC source to the distribution network or to a propulsion motor for a specified period. It is already connected to that grid and is supplied with all its auxiliary services. Using this converter to interface the energy store onto the bus therefore provides a solution with a minimum footprint within a vessel where space is at a premium. This is illustrated in Figure 3.

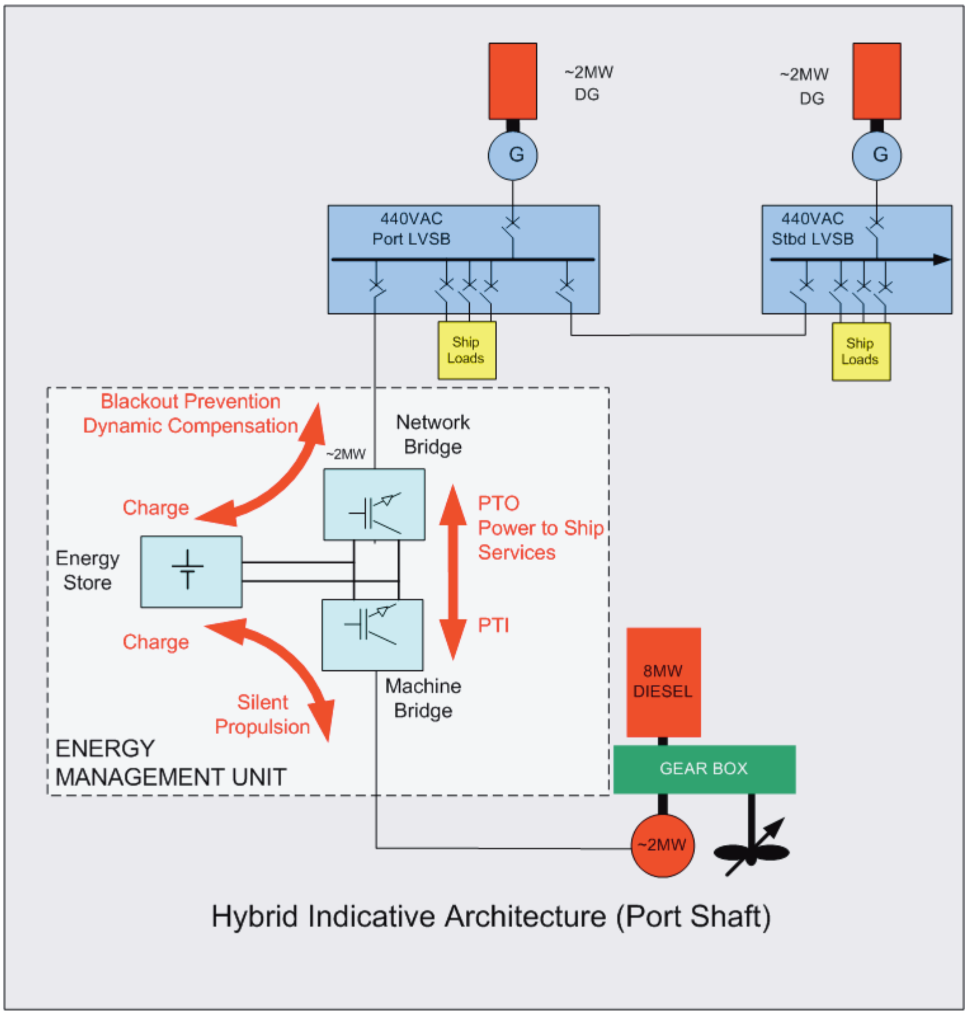

Figure 3 Energy Management Unit

Thus, the modern hybrid converter is evolving. The energy store enables the PTO converter to hold up the entire ship distribution network, even in the event of the loss of all prime movers. It also enables a complete dynamic decoupling of the network transients from the mechanical drive system this providing extremely high-quality power without stressing the propulsion mechanics. It is capable of managing power flow into an energy store while simultaneously driving the ship in PTI mode or of delivering emissions free, silent propulsion. This flexibility means that what had previously been considered as a “propulsion drive” is now becoming the heart of the energy management system of the vessel, significantly enhancing the survivability and flexibility benefits that the hybrid concept brings to the power and propulsion system.

6. Conclusion

Recently completed projects with hybrid propulsion have demonstrated advantages as well as some challenges encountered during system design, testing and operation. In addition to the flexibility that these projects demonstrate, the hybrid concept continues to evolve and the hybrid propulsion converter is emerging as the heart of the energy management system of vessels of the future.

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